THE EFFECT OF THINNING AND ASPECT ON FIRE BEHAVIOR IN THE MISSOURI OZARKS OF THE CENTRAL HARDWOOD REGION

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ABSTRACT

Prescribed fire and thinning are commonly used practices in glade–savanna–woodland restoration. However, little information exists on the effects of aspect or thinning on fire behavior or fuel loading in the Central Hardwood Region. Fire behavior (rate of spread and flame length), fuel loading, and consumption data were collected in the southeastern Missouri Ozarks to determine if aspect (north- and east-facing backslopes [protected], south- and west-facing backslopes [exposed], and ridges [no aspect, $<$8% slope]) or treatment (thin–burn versus burn only) had an effect on fire behavior. Fuel loading differed for 1000-h fuels by aspect for pre-treatment, post-thinning, and post-thinning–burn treatments. The general pattern was a progression from exposed slopes, to ridges, to protected slopes. Thinning increased total fuel loading about 300% (from 1.53–1.93 kg/m^2 to 5.04–6.36 kg/m^2), with 100- and 1000-h solid fuels replacing litter as the heaviest component of the total.

When burned, exposed and protected aspects exhibited greater average and maximum flame lengths and fireline intensities. Exposed aspects exhibited more intense fires compared to ridges and protected aspects. Heat per unit area and total energy release were mostly affected by treatment, not by aspect, with thin–burn treatments experiencing greater levels of both than the burn-only treatment. Comparative differences in fireline intensity, heat per unit area, and total energy release indicate that fireline intensity may be the best predictor of fire effects.

keywords: Central Hardwood Region, fire behavior, fuel loading, intensity, Missouri Ozarks, oak (*Quercus*), oak–pine (*Quercus–Pinus*).

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INTRODUCTION

Fire behavior, a product of fuels, weather, and topography, and its effects are important to foresters, fire managers, and ecologists alike for managing prescribed fire and suppression efforts. Fire managers use existing fuels and various weather parameters in formulating prescriptions to achieve certain fire behavior characteristics that meet management objectives (Johnson and Miyanishi 1995). The response of an ecosystem to disturbance is dependent on the severity, frequency, and size of the disturbance itself (Romme et al. 1998). In the case of fire, severity is a function of energy released, or intensity (Byram 1959, Brown and Davis 1973, Alexander 1982, Johnson and Miyanishi 1995).

Lack of quantification of fire behavior has been a major shortcoming in many studies of fire effects. However, measures that characterize fire behavior exist that correlate well with effects; the two most common measures used to characterize fire behavior are fireline intensity (FLI) and heat per unit area (HPA) (Rothermel and Deeming 1980, Alexander 1982, Johnson and Miyanishi 1995). FLI (kW/m) is the energy released

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by the flaming front over a given time; HPA (kJ/unit area) accounts for the amount of energy released per unit of area by the flaming front (Byram 1959, Brown and Davis 1973, Alexander 1982, Johnson and Miyanishi 1995). Another measure is total energy release (TER; kJ/unit area). TER accounts for both energy released by the flaming front and energy released by consumption after the flaming front (Byram 1959, Rothermel and Deeming 1980).

FLI has been used successfully for many years as a tool to guide wildfire suppression tactics (Rothermel 1972, Albini 1976, Anderson 1982). Though success has been mixed, attempts have been made to correlate fire behavior with ecosystem response. The understanding of the effects from one fire is good to fair while that of the ecological effects of multiple fires is poor to fair, at best (Agee 1997). Overall, natural ecosystem variability combined with the variability associated with fire behavior makes correlating fire behavior with ecosystem response difficult. However, fire behavior and effects are not so unique that generalizations are impossible (Rothermel and Deeming 1980, Agee 1997).

FLI is derived using one of two methods: 1) estimated flame length and 2) combining rate of spread (ROS) with fuel consumption and fuel ‘‘low heat’’ of combustion (Byram 1959, Rothermel and Deeming 1980, Alexander 1982, Nelson 1986). However, both methods have flaws. Flame length and ROS observations are extremely variable through time and space (Johnson 1982) and rely mostly on human observations, which can contain bias and perception error. Additionally, fuel consumption can erroneously include energy released after the passing of the fire front (Ryan 1981, Alexander 1982). Consequently, several methods have been developed to remove a significant portion of human subjectivity from fire behavior sampling. Ryan (1981), Simard et al. (1989), Finney and Martin (1992), and Kolaks et al. (2004*a*) have developed or evaluated the use of fire-retardant–treated cotton string or tin–lead solder as passive flame-height sensors. Blank and Simard (1983) and Simard et al. (1989) developed an algorithm that utilizes measurements from three buried timers to derive ROS and direction of fire spread across any triangle.

TER is calculated by multiplying the weight of all fuel consumed by the energy content of that fuel minus the heat of vaporization (Byram 1959, Alexander 1982). In some cases, the total energy released can be more important than fireline intensity (Rothermel and Deeming 1980). This situation is likely to occur where heavier fuels (2.54 cm diameter or greater) ignite and burn for a period of time after the passing of the flaming front. However, TER does not account for the rate of energy release, or intensity, associated with the flaming front and cannot be considered a part of residence time or FLI (Rothermel and Deeming 1980). The effects of two fires having identical TER measurements could be completely opposite based on the proportion of energy released during the short duration of the flaming front versus the longer duration of glowing combustion.

Fire behavior information from the Central Hardwood Region is needed because fire has long played a role in the development and maintenance of oak (*Quercus*) forests. Fire, or the lack thereof, has altered vegetation structure as well as midstory and overstory composition of most oak forests in the United States. Abrams (1992) and Nuzzo (1986) contend that prairies, woodlands, and savannas have, or are becoming, dense oak forests, while oak forests, in some instances, are becoming maple (*Acer*) forests on more mesic sites. In many instances, fire is being put back into these ecosystems to restore ‘‘natural’’ pre–European settlement conditions or to favor oak regeneration.

Introducing fire back into hardwood landscapes may seem like the logical answer to many management issues concerning oak forests, such as oak decline or successional replacement. However, reintroduction of fire is not without consequences. Although oak is resistant to fire-caused mortality, it is still susceptible to damage that can degrade the butt log, the most valuable portion of a tree (Paulsell 1957; Scowcroft 1965; Loomis 1973, 1974, 1977; Loomis and Paananen 1989; Regelbrugge and Smith 1994). Managers, under the impression that ‘‘cool’’ fires will not damage trees, typically utilize ‘‘cool’’ backing fires when conducting ‘‘fuel reduction’’ burns in hardwood forests. Conversely, burns for savanna or woodland restoration are typically ‘‘hot’’ headfires, so as to kill or damage a portion of the overstory to reduce basal area and stocking. However, qualitative descriptors such as ‘‘hot’’ or ‘‘cool’’ are often difficult to correlate with ecologic response (Rothermel and Deeming 1980, Alexander 1982, Johnson and Miyanishi 1995). It is quite possible that backing fires may apply the same, or even more, heat to an area due to slower rates of spread and longer residence times.

Purpose

In an attempt to better quantify fire behavior under known fuel and weather conditions, we collected fire behavior data during prescribed burns in the Central Hardwood Region of Missouri. This project was part of a larger cooperative study funded by the Joint Fire Science Program. The project cooperators included the USDA Forest Service North Central Research Station, U.S. Geological Survey Northern Prairie Wildlife Research Center, University of Missouri-Columbia, and the Missouri Department of Conservation. The purposes of this study were to determine existing fuel loads and whether aspect (south- and west-facing slopes [exposed], no aspect [ridge], and north- and east-facing slopes [protected]) affected fuel loading, and fire behavior where applicable, in stands that received thinning, prescribed fire, both thinning and prescribed fire, or no management (control).

STUDY AREA

The study area was located in the southeastern Missouri Ozarks near Ellington, Missouri (lat 37.242°N, long 90.969°W), on land managed by the

Missouri Department of Conservation (Figure 1). In an effort to minimize variation caused by potential vegetation differences, study sites were all located within the Black River Oak/Pine Woodland/Forest Hills Landtype Association (Black River Hills LTA) per the Missouri Ecological Classification System (Meinert et al. 1997, Nigh and Shroeder 2002). The Black River Hills LTA, characterized by strongly rolling to hilly lands with steep slopes and flat land found only in creek and river bottoms, historically comprised oak and oak–pine (*Quercus*–*Pinus*) woodlands and forests. These forest types still dominated but were second growth and had grown more closed due to fire suppression (Nigh and Shroeder 2002). The Black River Hills LTA was in the center of one of the largest blocks of forest in the Midwest that also supports a substantial timber industry (Nigh et al. 2000).

METHODS

Site Selection

Stands selected for the study had no known forest management activities or wildfire for at least 30 y. All stands were fully stocked (average basal area of 9.75 m^2 [105 ft^2] and 874 trees/ha [354 trees/acre]) according to Gingrich (1967) (average 92%) and composed primarily of oak–hickory (*Quercus*–*Carya*) and oak–pine forest types. Treatments were replicated across 3 complete blocks. Each block had 12 stands (3 aspect classes and 4 treatments), with each stand being an aspect–treatment unit. Stand area ranged from 3 to 6 ha (12–15 acres). Aspect classes included exposed backslopes (135–315°), ridge, and protected backslopes (315–135°) (Nigh et al. 2000).

Treatments

Treatments were randomly assigned on the study sites and included commercial thinning, prescribed burning, both commercial thinning and prescribed burning, and no treatment (control). Commercial thinning of the overstory occurred during the summer and early fall 2002. Leave-tree preference was given to individuals having relative fire tolerance, good form, and canopy dominance. A mark–leave method was utilized to select leave trees. Merchantable unmarked trees were felled and logs skidded to landings for processing prior to removal from the site. Tops were left in place along with cull sections of logs. Any remaining unmarked trees with diameter at breast height (dbh) $>$3.5 cm were cut after the harvest was complete. In addition to mechanical harvest, windthrow aided in reducing stocking to 41% (average basal area of 3.9 m^2 [50 ft^2] and 217 trees/ha [155 trees/acre]) according to the Gingrich (1967) stocking chart. The target stocking level was 60% because it is commonly used in intermediate cuttings, shelterwood systems, and savanna–woodland restoration (Johnson et al. 2002).

Prescribed burns were conducted during spring 2003, using prescription conditions common in the Missouri Ozarks (Table 1). Prescribed burns were ignited with a ring-fire method while simultaneously igniting the ridges. This firing method was used because it is the most common firing technique in the region. The objectives of the prescription were to reduce fuels and kill woody stems $<$3.81 cm dbh.

Data Collection

Fuel Loading

We inventoried fuels using a modified transect intercept method with a transect emanating in a random direction from 15 random points within each stand. Pre-thinning data were collected in winter 2002. Post-thinning and pre-burn data were collected during winter 2003. Post-burn sampling was completed after the burns in spring 2003 (Kolaks et al. 2003, 2004*b*). Woody fuels were separated into four size classes: 0.0–0.64 cm (1-h), 0.64–2.5 cm (10-h), 2.5–7.6 cm (100-h), and $>$7.6 cm (1000-h). The 1000-h fuels were further separated into *rotten* and *solid* categories. From each sample point, 1- and 10-h fuels were inventoried along a 1.8-m segment, 100-h fuels along a 3.7-m segment, and 1000-h fuels along the entire 15.2-m length of the transect. Fuel height and litter and duff depths were measured at 1.5-m intervals along the fuel transect, starting 0.3 m from the origin (Brown 1974, Brown et al. 1982, Grabner 1996, National Park Service 2001). Litter and herbaceous samples were collected from a 0.2-m^2 (2-ft^2) clip-plot located at the end of each fuel transect. Samples were then dried at 60°C to a constant weight and reported on a dry-weight basis (Grabner 1996).

Fuel Consumption

Fuel consumption was calculated for each time-lag class at the transect level. Post-burn fuel loading was subtracted from pre-burn fuel loading (Kolaks et al. 2004*b*). In rare instances, fuel loading in given time-lag class increased because of incomplete combustion of fuels in the next largest time-lag class (e.g., a 100-h fuel partially consumes to the size of a 10-h fuel). For the analysis, negative consumption values were ignored.

Rate of Spread, Flame Height, and Flame Tilt Angle

Modified ROS clocks and passive flame-height sensors were used to collect ROS data and flame-height data from three randomly chosen points out of the 15 preexisting points within each stand. In order to objectively determine flame length, two measures were recorded at each point. First, flame height was recorded by an array of passive flame-height sensors calibrated for the Central Hardwood Region (Kolaks et al. 2004*a*). Each array comprised 12 strands of fire-retardant–treated cotton string suspended between two wires, one at fuel bed height and the other approximately 2.3 m above the fuel bed. Second, trained observers used visual aids (the clinometer in a Silva Ranger® compass and a clear sheet of plastic equipped

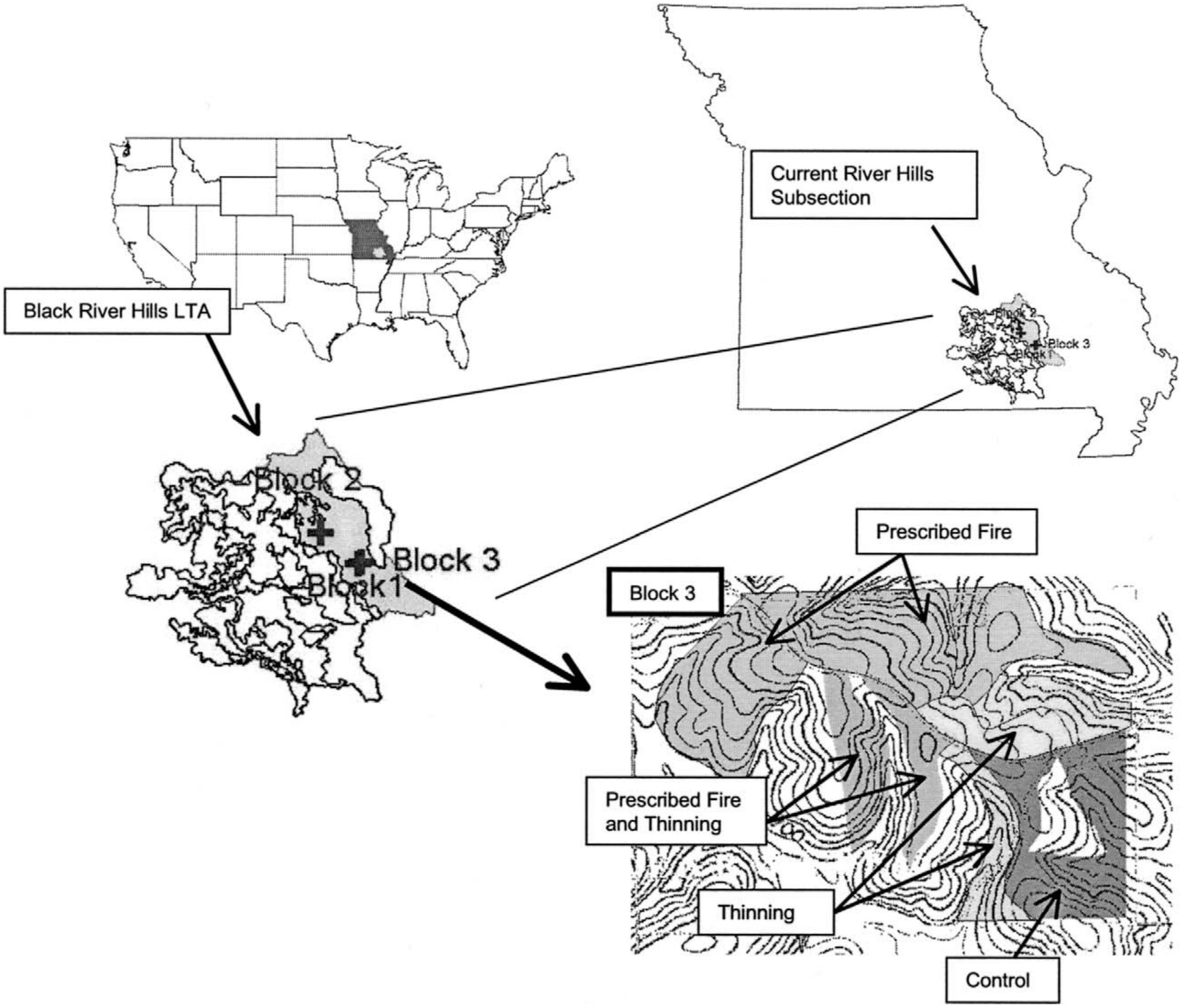

Fig. 1. Location of study sites and arrangements of treatments (block 3 used as an example) in forest stands treated with prescribed fire or with both thinning and prescribed fire, Central Hardwood Region, Missouri Ozarks, 2002–2003.

with a bubble level and marked with various angles from 0 to 90°) to determine flame-tilt angle as the fire front passed through the flame-height sensor arrays. Flame-tilt angle, which is combined with flame height to derive flame length, can be measured at a greater distance by fewer observers than direct observation of flame length (Ryan 1981).

Average flame lengths (AFLs) were then derived by averaging flame heights indicated by sensors in each array (Kolaks et al. 2004*a*) and applying the corresponding flame-tilt angle (Ryan 1981). Estimated maximum flame length (MFL) was derived using the tallest flame height recorded by a sensor array and applying the flame-tilt angle. These methods eliminated a large component of variation imposed via human observations by removing subjectivity and perception discrepancies.

To measure ROS, five clocks were located at each point, one at the point and the others 15.24 m in each cardinal or sub-cardinal (NE, SW, etc.) direction, depending on the locations of fire-spread obstructions such as logs and rock outcroppings. ROS and direction were calculated using at least three measurements from the buried clocks (Simard et al. 1984). Unfortunately, only a fraction of the ROS clocks worked properly. Over two-thirds of the clocks endured cold temperatures and precipitation for several days after the burn

Table 1. Weather parameters and fuel moisture prescription used for prescribed burning and observed values in forest stands treated with prescribed fire or both thinning and prescribed fire, Central Hardwood Region, Missouri Ozarks, 2002–2003.

Parameter	Prescription	Observed	
		Average	Range
Temperature (°C)	7–18	18	7–28
Mid-flame wind (m/s)	0–3.1	1.1	0–3.4
Relative humidity (%)	25–45	22.4	9–46
Percent fuel moisture			
1-h	5–10	5.4	5–6
10-h	8–15	9.8	8–12
100-h	12–18	13.7	13–18
1,000-h	>20	17.6	17–20

due to circumstances beyond our control. Clocks recovered immediately after the burn worked properly and provided good data. However, sufficient data were not available to conduct statistical analysis. Given that the FLI can be determined by two methods, and that the two methods are correlated with each other (Byram 1959, Nelson 1986), estimates of ROS were derived by dividing FLI by energy released by 1-h woody and litter fuels (Equation 1). We assumed that only litter and 1-h woody fuels were consumed by flaming front. Given that $I = HWR$ (Byram 1959), then

$$R = I/HW \tag{1}$$

where R = rate of spread (m/s), I = FLI (kW/m), H = low heat of combustion (18,577 kJ/kg [adjusted for heat of vaporization]), and W = weight of fuel consumed (1-h woody and litter [kg]).

Environmental Measurements

Weather parameters, including eye-level wind speed and direction, 10-h fuel moisture and temperature, relative humidity (RH), and air temperature, were measured and recorded every 15 min with a Campbell® Scientific automated weather station (Campbell Scientific, Logan, UT). The station was placed on a ridge upwind and adjacent to the sites under the leafless canopy. One-, 100-, and 1000-h fuel moistures were calculated using data from two automated weather stations that experienced similar weather patterns located in relatively close proximity (15 and 24 km) to the study sites.

Fireline Intensity, Heat Per Unit Area, and Total Energy Release

FLI and HPA were calculated using average flame lengths for each of the fire behavior plots. Byram's (1959) FLI equation was used (Equation 2):

$$\mathrm{FLI} = 258F_{\mathrm{L}}^{2.17}, \tag{2}$$

where FLI = fireline intensity and F_{L} = flame length (m). HPA (Equation 3 [Rothermel and Deeming 1980]) was calculated using the estimated ROS (Equation 1) for each of the fire behavior points. Using average flame length alleviates issues associated with consumption of fuels after the passing of the flaming front.

$$H_{\mathrm{A}} = (60I)/R, \tag{3}$$

where H_{A} = heat per unit area (kJ/m²), I = FLI (kW/m), and R = rate of spread (m/min).

To obtain TER, post-burn fuel loading was subtracted from pre-burn fuel loading (Kolaks et al. 2004*b*). Using methods outlined by Byram (1959) and Brown and Davis (1973), TER was derived for each time-lag class (Equation 4):

$$\begin{aligned}\mathrm{TER} = {} & \text{weight of fuel consumed} \\ & \times (\text{heat of combustion for oak} \\ & - \text{heat of vaporization}),\end{aligned} \tag{4}$$

where heat of combustion for oak = 19,215 kJ/oven-dry kg, and heat of vaporization = 24 kJ × (% fuel moisture) + 573 kJ. Fuel moisture was assumed to be applicable over the entire site for a given day. TER was then grouped into 1-h fuel loading (litter and 1-h woody fuels), all fuel, and the percentage of total TER that was released by 1-h fuels. A reduction for radiation, suggested by the original methodology (Byram 1959), was not made because there is no sound basis available for estimating radiant heat as a proportion of the total energy output, and heat ''losses'' from radiation actually contribute greatly to fire behavior (Alexander 1982).

(All intensities are reported in kilojoules despite British thermal units [Btu] being the most common output used by management models for FLI. However, FLI can be easily converted from kW/m to Btu/ft per second by dividing by 3.4592 [Alexander 1982]. HPA, TER, and 1-h TER can be divided by 1.0551 to derive Btu/ft².)

Data Analysis

Analysis of variance was used to determine if differences in fuel loading and fire behavior differed due to treatment and aspect. Data were analyzed using the MIXED procedure in SAS (SAS Institute, Cary, NC). This procedure was used because it allows covariates to vary within a subject (Wolfinger and Chang 1995). We used $\alpha \leq 0.05$ to test differences among aspects, treatment, and aspect–treatment interactions in TER. Because we did not include weather factors or slope as explanatory variables, and because of fire behavior's variable nature, $\alpha \leq 0.10$ was used for the same differences in AFL, MFL, and HPA.

RESULTS AND DISCUSSION

Although data may appear conclusive, it is important to remember that, due to the variable nature of fire behavior, the results of this study are only representative of the given fuel conditions, weather, and topographic conditions. Variables not taken into account during this analysis, such as possible differences in slope of the protected and exposed backslopes, may account for some variation. Dormant-season ''canopy covers'' can also differ between stands, allowing for differing solar insulation between stands within an aspect class. Burning under any other conditions, even the same fuel conditions with different weather conditions, may yield surprisingly different results. Furthermore, the estimation of ROS from the back-calculation of an empirical formula should cast a degree of uncertainty on HPA.

For the most part, all burns were conducted within prescription. Average RH was below prescription, but ignition operations were completed before the RH dropped below the lower threshold (Table 1). Although prevailing wind direction for the Missouri Ozarks is south or southwest, winds were primarily out of the north–northwest during the burning period. Because exposed slopes are typically drier (Nigh et al. 2000), differences in all fire behavior parameters, especially between exposed and protected backslopes, may have been more pronounced had there been a southerly wind.

Fuel Loading and Consumption

Data for fuel loading and consumption were presented in Kolaks et al. (2004*b*). In unthinned stands, total fuel loading varied from 1.53 to 1.93 kg/m^2 (Kolaks et al. 2004*b*). Significantly different loading due to aspect was only present in 1000-h solid fuels. All other time-lag classes, including fine fuels (litter and 1-h woody), did not significantly vary by aspect (Kolaks et al. 2003).

In thinned stands, total fuel loading ranged from 5.04 to 6.36 kg/m^2 (Kolaks et al. 2004*b*). Significant differences did not exist in fine fuels between aspects. However, significant differences existed in the 10-h time-lag class between exposed backslopes and ridges, and the 100-h time-lag class between exposed slopes and both ridges and protected slopes. On average, fuel height was 26.7 cm greater while litter depth was 2.5 cm lower following thinning (Kolaks et al. 2004*b*).

Average and Maximum Flame Length

As a whole, aspect significantly impacted AFL. On average, AFL was greater on the backslopes than on ridges, with exposed backslopes having significantly greater flame lengths than ridges and protected backslopes ($P = 0.010$ and 0.083, respectively) (Table 2). AFL was also significantly different among aspects within the thin–burn treatment, with exposed slopes being significantly greater than ridges and protected slopes ($P = 0.012$ and 0.064, respectively). However, despite similar differences between aspects in the burn-only treatment, high variability masked any potential difference. On average, AFL was greater for the thin–burn treatment compared to the burn-only treatment, albeit not significant.

Estimated MFL behaved similarly to AFL. Overall, MFL was greater on backslopes than on ridges, with exposed backslopes having significantly greater flame lengths than ridges and protected slopes ($P = 0.006$ and 0.082, respectively). MFL was also significantly different among aspects within the thin–burn treatment, with exposed slopes being significantly greater than ridges and protected slopes ($P = 0.005$ and 0.025, respectively) while not being significantly different among any aspect class in the burn-only treatment. Significant treatment differences within aspect class were not detected except for exposed slopes, with the thin–burn treatment having significantly greater MFL than the burn-only treatment ($P = 0.038$) (Table 2).

Despite exposed slopes having significantly less fuel loading in the 100-h time-lag category, significantly greater average and maximum flame lengths occurred on exposed backslopes than on ridges or protected backslopes. This could be attributed to drier fuels due to solar exposure. Again, a southerly wind may have created a more pronounced difference between exposed and protected slopes.

Table 2. Fire behavior characteristics by aspect and treatment in forest stands treated with prescribed fire or both thinning and prescribed fire, Central Hardwood Region, Missouri Ozarks, 2002–2003. Different letters indicate significant difference within a row (lowercase) or column (uppercase).

Treatment	Aspect			Treatment average
	Exposed	Ridge	Protected	
Average flame length (m)				
Burn	0.54aA	0.30aA	0.45aA	0.44A
Thin–burn	0.86aA	0.35bA	0.52bA	0.58A
Aspect average	0.72a	0.33b	0.49b	
Estimated maximum flame height (m)				
Burn	1.73aA	0.90aA	1.62aA	1.42A
Burn–thin	2.98aB	1.1bA	1.55bA	1.89A
Aspect average	2.36a	1.00b	1.61b	
Byram's fireline intensity (kW/m)				
Burn	100aA	21a	62a	62A
Burn–thin	242aB	42b	118b	131A
Aspect average	170a	35b	26b	
Heat per unit area (kW/m^2)				
Burn	1,166A	1,196A	1,011aA	1,136A
Burn–thin	1,227bA	1,330A	1,448acB	1,335B
Aspect average	1,197	1,263a	1,262a	
Total energy release (TER) (kJ/m^2)				
Burn	2,592aA	2,579aA	2,485aA	2,552A
Burn–thin	3,542aB	3,610aB	3,788aB	3,656B
Aspect average	3,066a	3,136a	3,110a	
1-h TER (kJ/m^2)				
Burn	2,251aA	2,273aA	2,145aA	2,222A
Burn–thin	2,302aA	2,386aA	2,486aB	2,391B
Aspect average	2,276a	2,330a	2,317a	
TER accounted for by 1-h fuels (%)				
Burn	80aA	85aA	84aA	83A
Burn–thin	62aA	77aA	68aA	69B
Aspect average	71a	81a	76a	

Average and maximum flame lengths in thinned stands did not accurately reflect the average across the entire stand. Passive flame-height sensors could not be installed through logging slash. Rather, AFLs more accurately depict the areas between slash piles as the thinning influenced them. The trained observers visually estimated flame lengths off of slash. Estimates included average and maximum flame lengths. In general, flame lengths from slash averaged 4.3 m, with MFLs of 15.2 m being common.

Fireline Intensity

Because FLI was derived from flame length, FLI behaved almost identical to flame length. Treatments (excluding slash flame-length data) did not significantly affect FLI, despite a minor difference of 19 kW/m (Table 2). On average, overall FLI was greater on backslopes than on ridges; exposed backslopes had a significantly greater FLI than ridges and protected slopes ($P = 0.025$). FLI was also significantly greater by aspect in the thin–burn treatment, with exposed slopes having significantly greater intensities than ridges and protected slopes ($P = 0.017$ and 0.100, respectively), while not being significantly different from any aspect class in the burn-only treatment. Despite the thin–burn treatment having greater FLI than the burn-only treatments by a magnitude of 2 on average, treatments were significantly different only on exposed slopes ($P = 0.025$) (Table 2).

Heat Per Unit Area

HPA was only significantly affected by aspect in the thin–burn treatment. Significant differences within an aspect class due to treatment only occurred on protected slopes. Overall, the thin–burn treatment had a greater HPA than the burn-only treatment (Table 2). Differences are difficult to attribute because ROS, a divisor in calculating HPA, was calculated from FLI. The overall difference between treatments can be attributed to obviously greater fuel loads in thinned stands and could be greater than indicated because average flame length, used in the calculation of FLI, did not include the flame lengths off of slash. The difference in HPA on protected slopes between treatments is most likely the result of greater contributions of fuel from thinning on protected slopes compared to exposed slopes (Kolaks et al. 2004*b*).

Although significant differences existed between aspect classes in the thin–burn treatment ($P = 0.017$), the overall difference between aspects did not exceed 221 kW/m^2. Since HPA ranged from 1,089 to 1,441 kW/m^2, the significance of a 221-kW/m^2 difference on ecological response is unknown. However, on protected slopes, we saw a change of nearly 402 kW/m^2 difference between treatments ($P = 0.009$). Differences in HPA between slopes may be the result of weather conditions (i.e., north wind) or time of the burning period (i.e., drier portion of the day). A difference between treatments could be attributed to greater fuel loading in thinned stands where the thin–burn treatment received almost one-third more heat than the burn-only treatment on protected backslopes. Though the importance of this contrast is unknown, a difference in ecological response would not be surprising on protected backslopes between treatments.

Within treatments, the ridges received almost identical HPA as the backslopes. The lack of difference in HPA between backslopes and ridges (Table 2), despite the significant difference between the backslopes and ridges in AFL and FLI (Table 2), indicate that a backing or slower-moving fire may not actually be a ‘‘cool’’ fire.

Total Energy Release

TER was significantly higher in the thin–burn treatment compared to the burn-only treatment in every aspect class and overall by treatment (Table 2), which can be attributed to the greater availability of fuels after thinning. There were no significant or nearly significant differences as a result of aspect, despite differences in flame length and FLI. The lack of difference due to aspect indicates that FLI or flame length may not have a bearing on consumption.

One-hour TER responded to treatment similarly, but to a lesser degree than TER, likely a result of the minor contribution of 10-h time-lag fuels in the combustion process. Overall, the thin–burn treatment was significantly greater than the burn-only treatment ($P = 0.001$). Within aspect class, the thin–burn treatment was significantly greater than the burn-only treatment on protected aspect class only ($P = 0.033$) (Table 2).

The percentage of TER accounted for by 1-h TER was significantly different overall by treatment ($P = 0.022$), with 1-h fuels (litter and 1-h woody) being responsible for an average of 83% of TER in the burn-only treatment and 69% in the thin–burn treatment (Table 2). One-hour fuels accounted for 38–52% of total fuel loading in unthinned stands and 13–15% of total fuel loading in thinned stands (Kolaks et al. 2003, 2004*b*). This suggests that, despite large amounts of heavy fuel (100-h and greater), 1-h fuels have the greatest influence on fire behavior and energy release (Byram 1959, Davis 1959) under typical prescribed burning conditions (Table 1). Brown (1972) found similar results with fuel $<$1 cm (0.39 inch) in diameter accounting for $<$30% of the total loading and half of the total weight loss in ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) slash fires. Furthermore, for slash and other fuels containing a similar mixture of particle sizes, particles $<$2.54 cm (1 inch) in diameter essentially provide the energy that characterizes propagation of the flaming front.

Despite fine fuels having the greatest impact on characteristics of fire behavior, the proportion of energy released by heavy fuels may be just as, or even more, important (Rothermel and Deeming 1980). Anderson (1969) found that residence time in minutes was equal to 3.15 times the particle diameter in centimeters. Increased consumption of larger fuels, as was the case in the thin–burn treatment, would indicate longer residence times from either open flame or glowing combustion (Kolaks et al. 2004*b*).

MANAGEMENT IMPLICATIONS

When relating FLI, HPA, and possibly TER to fire effects on components of an ecosystem, such as trees, it is important to consider that components of the ecosystem may be more or less resistant to different amounts of heat for different periods of time. It is also important to note that this resistance may change according to age, season, or other environmental conditions such as drought (Whelan 1995). Past research in oak–hickory forests of the Central Hardwood Region indicate that top-kill, mortality, and damage are highly correlated and directly related to the height of stem-bark char and inversely related to diameter at breast height (Paulsell 1957; Scowcroft 1965; Loomis 1973, 1974; Loomis and Paananen 1989; Regelbrugge and Smith 1994). Height of stem-bark char can be correlated with flame height and length (Cain 1984), and subsequently correlated with FLI (Byram 1959, Alexander 1982, Nelson 1986). Given that higher stem-bark char would indicate greater FLI, these variables suggest that oak–hickory forest trees may be more resistant to low heat for longer periods of time (low-intensity fires), as opposed to high levels of heat for shorter periods of time (high-intensity fires), even though both situations may be indicative of near-identical HPA and TER. Further, this suggests that FLI may be a better predictive variable for fire effects than HPA or TER.

Other woody and herbaceous plants may respond similarly or differently depending their methods or pathways of ‘‘resistance.’’ Future study of these responses will not only need to account for fire behavior measures independent of each other, but also the response to varying combinations of fire behavior measures (i.e., high FLI versus low HPA). These measures combined with the biologic and physical environment of a burn can aid greatly in the explanation of fire effects.

CONCLUSION

When utilizing a ring-headfire-ignition method, differences among aspects in flame length and FLI may have significant impact on planning, suppression efforts, and ecological response, despite HPA and TER not varying greatly. Increased flame length and FLI on backslopes indicate that control lines for prescribed and wildland fires should be placed on ridges, not on slopes, especially where fire will impinge from below. Also, given that flame lengths of slash piles averaged 4.2 m (14 ft), with a maximum of 15.2 m (50 ft), control lines should be located a sufficient distance away from such fuels to reduce the chance of spot fires.

HPA and TER were affected most by treatment, with little effect due to aspect. It is possible that a backing fire could have greater impact than a headfire given longer residence times for backing fires. Managers, ecologists, and researchers alike should evaluate these discrepancies, especially in HPA versus FLI, between different fire behaviors (i.e., head and backing) caused by ignition techniques. We think FLI may be the best predictor of fire effects within homogeneous fuel conditions, given that it varied due to slope, whereas HPA and TER did not. Also, because litter and 1-h woody fuels (1-h fuels) account for the greatest proportion of energy released during a fire, they will have the greatest effect on FLI and HPA, despite total fuel loading.

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